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INVESTIGATION OF THE EFFECTS OF AIR INJECTION UPON THE HYPERSONIC LAMINAR BOUNDARY LAYER

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ARO, Inc.

April 1966

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NOTICES

INVESTIGATION OF THE EFFECTS OF AIR INJECTION UPON THE HYPERSONIC LAMINAR BOUNDARY LAYER

R. L. Palko and A. D. Ray
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FOREWORD

The work reported herein was conducted for The Boeing Company, Seattle, at the request of the Air Force Flight Dynamics Laboratory (AFFDL), Research and Technology Division (RTD), Air Force Systems Command (AFSC), under Program Element 62405334, Project 1366, Task 136606.

The results of the tests were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract AF40(600)-1200. The tests were conducted from September 20, 1965, to January 27, 1966, under ARO Project No. VT0510, and the manuscript was submitted for publication on March 24, 1966.

This technical report has been reviewed and is approved.

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ABSTRACT

An experimental study was conducted to obtain boundary-layer pitot pressure profile data on a sharp and a blunt leading edge rectangular plate and a sharp leading edge delta wing at Mach 6, 8, and 10. Effects of Reynolds number, angle of attack, and mass injection were studied. Selected results are presented to illustrate the effect of air injection upon the sharp rectangular plate boundary layer at Mach 8 and zero angle of attack.

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NOMENCLATURE

M_∞	Free-stream Mach number
p_o	Stagnation pressure, psia
p_o'	Total pressure behind a normal shock, psia
p_{t_p}	Probe total pressure, psia
p_w	Model surface pressure, psia
p_∞	Free-stream static pressure, psia
Re_∞	Free-stream unit Reynolds number, in.$^{-1}$
T_o	Stagnation temperature, °R
T_w	Model surface temperature, °R
x	Longitudinal distance along model surface, in.
y	Vertical distance above model surface, in.
z	Lateral distance along model surface, in.

SECTION I
INTRODUCTION

Pitot and surface pressure and surface temperature measurements were made on a flat rectangular plate and a flat delta plate at Mach numbers of 6, 8, and 10. The tests were performed in the 50-in. hypersonic tunnels (Gas Dynamic Wind Tunnels, Hypersonic (B) and (C)). The objective of the tests was to obtain boundary-layer pitot pressure profile data to help verify an analytical method under development by The Boeing Company for predicting minimum critical Reynolds number (below which boundary-layer transition cannot occur) in hypersonic flow.

To supply comparison data for use in the analytical method, small amounts of air were injected into the boundary layer to produce very small magnitude artificial disturbances. Boundary-layer pitot pressure profile data, measured near the downstream end of the plate, were used to determine the extent to which the boundary layer was disturbed. Some other parameters which were studied were the effects of free-stream Reynolds number and angle of attack.

SECTION II
APPARATUS

2.1 WIND TUNNELS

Tunnels B and C are axisymmetric, continuous flow, variable density wind tunnels with 50-in.-diam test sections (Fig. 1 and Ref. 1). Tunnel B has interchangeable throat sections which produce nominal Mach numbers of 6 and 8. The tunnel operates at stagnation pressures from 20 to 300 psia at Mach 6 and from 50 to 900 psia at Mach 8. Stagnation temperatures up to 1350°R are utilized to prevent liquefaction of the air in the test section.

Tunnel C operates at a nominal Mach number of 10 at stagnation pressures from 200 to 1800 psia. Stagnation temperatures up to 1900°R are utilized to prevent air liquefaction.

2.2 MODELS

The models, furnished by The Boeing Company, consisted of two flat stainless steel plates (Fig. 2), one rectangular in shape (20 x 28 in.)

and the other delta in shape (34 in. long). The rectangular model had interchangeable leading edges of 0.002- and 0.25-in. diameter, whereas the delta model had fixed 0.002-in.-diam leading edges. The instrumented surfaces of the models were 1/4-in. stainless steel plates. Both models were instrumented with surface pressure taps and thermocouples and were sting mounted in the tunnels. The Chromel®-Alumel® thermocouples were tack welded to the back of the 1/4-in. surface plate. Ports for air injection were located at several places along the centerline of both models to artificially disturb the boundary layer.

2.3 SURVEY PROBE

The pitot survey probe was capable of traversing in the x, y, and z planes. The outer diameter of the probe tip used during the surveys was 0.032 in.

A fouling light was used to indicate contact between probe and model surface for determining the "y" zero. The "y" zero was repeatable within 0.002 in.

2.4 INSTRUMENTATION

Model surface pressures were measured in Tunnel B with 15-psid transducers, whereas in Tunnel C, 1- and 15-psid transducers were switched in and out of the system automatically to allow measuring to better precision. The estimated precision of the Tunnel B measurements is ±0.003 psia or 1 percent, and in Tunnel C is ±0.001 psia or 1 percent, whichever is larger.

The probe pressure was measured with a 5-psid transducer, using a variable reference pressure, which allowed measurements within a precision of ±0.002 psia or 1 percent, whichever is larger.

The reference junction of the surface temperature thermocouples was maintained at 132°F. The temperature measurements are estimated to be accurate within ±2 deg.

The mass flow for the injection ports was measured using calibrated orifices in a flowmeter. The pressure upstream of the orifice and the differential pressure across the orifice were measured with a 100- and a 50-psid FM transducer, respectively. The supply air to the flowmeter was maintained at room temperature. Based upon calibrations of the flowmeter and upstream-pressure transducer, the precision of the mass flow measurement is estimated to be ±5 percent.

SECTION III
PROCEDURE

The tests were conducted at nominal Mach numbers of 6, 8, and 10 at stagnation pressures of 20 to 285 psia, 100 to 900 psia, and 600 to 1800 psia, respectively. A complete tabulation of the test conditions is given in Table I.

References 2 and 3 were used to determine preliminary tunnel and model conditions to ensure that laminar flow existed over the model for the mass injection tests. To verify the condition of the flow, the probe was traversed along the surface of the model in the "x" direction and stopped at selected intervals to measure pitot-probe pressure.

SECTION IV
RESULTS AND DISCUSSION

To obtain comparison data for the Boeing analytical method, it was necessary to obtain pitot pressure profiles under conditions of an artificial disturbance. The use of air injection was chosen in order that the method of disturbing the boundary layer could be closely controlled and the exact conditions could be used in the analytical program.

Data were obtained for two variations in the air injection procedure. One was to inject air at different mass flow rates from one location and measure boundary-layer pitot pressure profiles at each mass flow rate (Fig. 3). As shown in the figure, the lower mass injection rate (10×10^{-6} lb_m-sec^{-1}) had little or no effect on the profile measured near the rear of the sharp rectangular plate. However, deviations did occur when the flow rate was increased to 20×10^{-6} and 50×10^{-6} lb_m-sec^{-1}. Surface pressure and temperature distributions are shown at the bottom of the figure to illustrate typical levels of these data recorded at Mach 8.

The second variation (Fig. 4) was to inject at the same mass flow rate from different injection ports. As illustrated in Fig. 4, the location of the injection port has little influence upon the boundary-layer pitot pressure profile measured at a station near the end of the plate. Injecting air at a rate of 6.7×10^{-6} lb_m-sec^{-1} from ports located 2 and 11 in. aft of the leading edge had no effect upon the profile, and injection at a rate of 14×10^{-6} lb_m-sec^{-1} from either port produced about the same effect.

The effect of unit Reynolds number at Mach 8 on the sharp rectangular model is shown in Fig. 5. Here the trends are as expected, with the lower Reynolds number data, which was the base condition for the two figures previously discussed, showing a laminar profile and the higher Reynolds number data showing that transition has begun.

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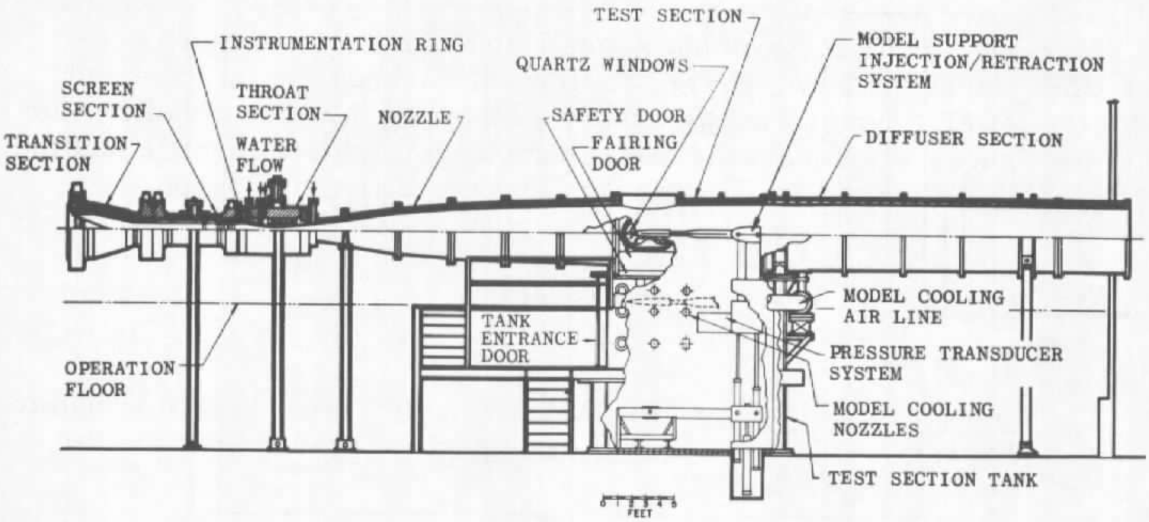
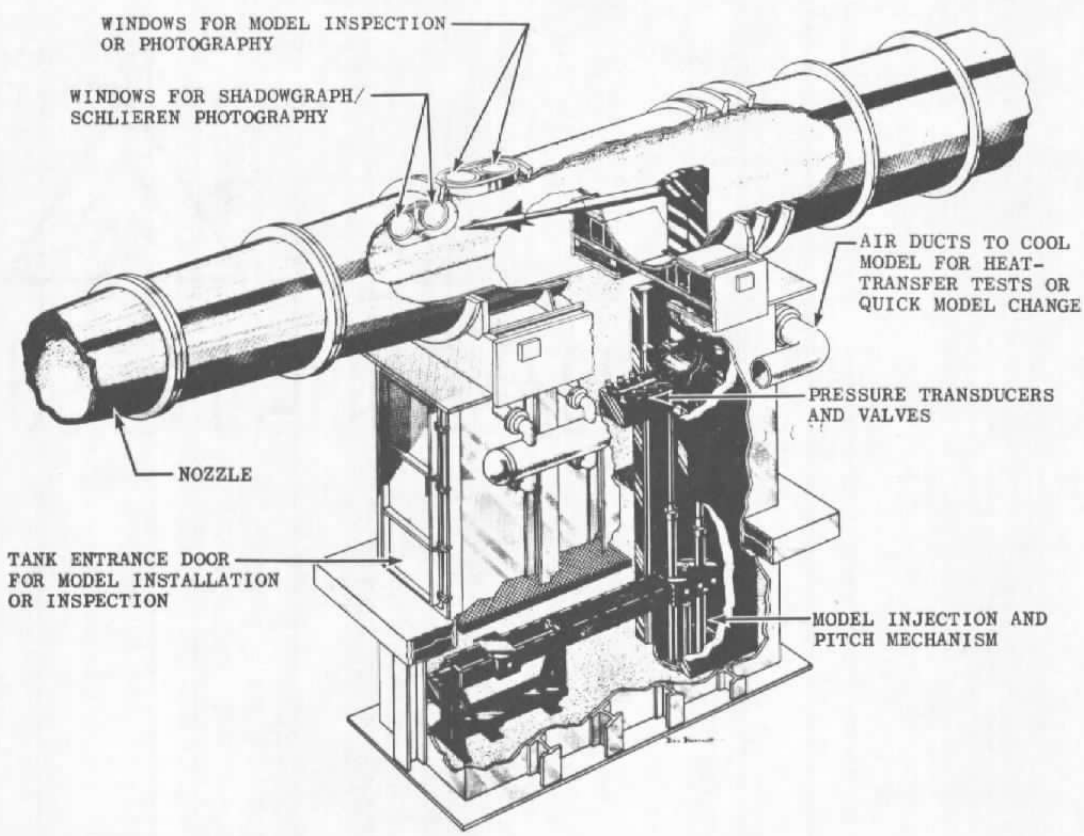
3. Deem, R. E., Erickson, C. R., and Murphy, J. S. "Flat-Plate Boundary-Layer Transition at Hypersonic Speeds." FDL-TDR-64-129, October 1964.

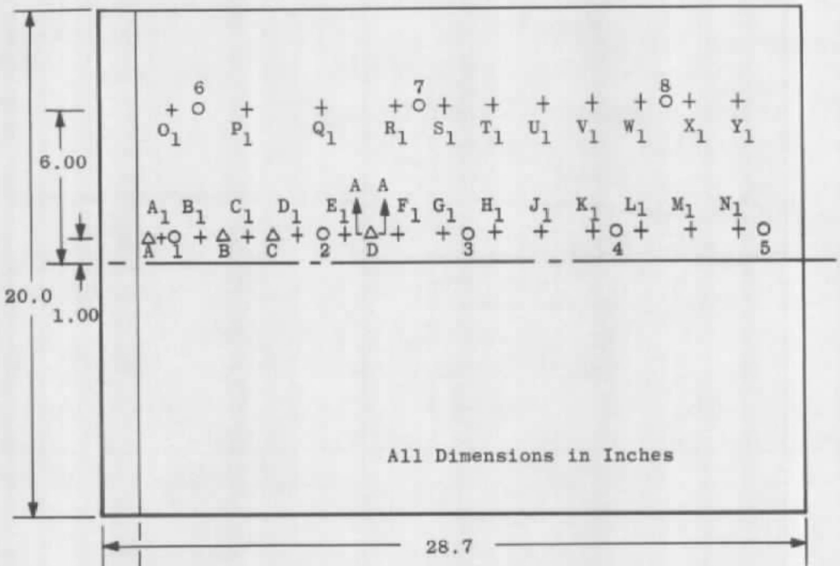


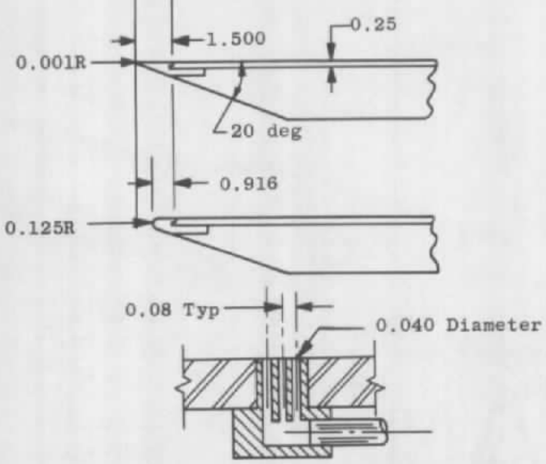
Tunnel Assembly



Tunnel Test Section

Fig. 1 Wind Tunnels





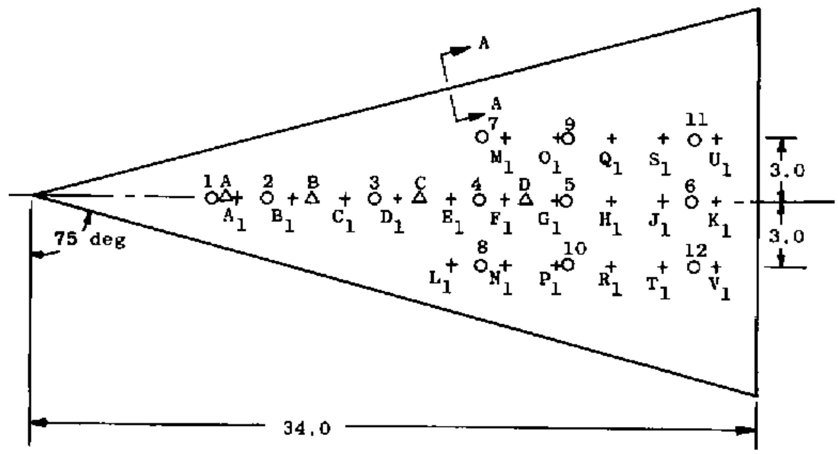
Typical Injection Port
Section A-A

○ Pressure Tap
△ Mass Injection Port
+ Thermocouple

Instrument Number	x, in.	Type Instrument
1	3.0	Pressure
2	9.0	
3	15.0	
4	21.0	
5	27.0	
6	4.0	
7	13.0	
8	23.0	
A	2.0	Injection Port
B	5.0	
C	7.0	
D	11.0	
A_1	2.5	Thermocouple
B_1	4.0	
C_1	6.0	
D_1	8.0	
E_1	10.0	
F_1	12.0	
G_1	14.0	
H_1	16.0	
J_1	18.0	
K_1	20.0	
L_1	22.0	
M_1	24.0	
N_1	26.0	
O_1	3.0	
P_1	6.0	
Q_1	9.0	
R_1	12.0	
S_1	14.0	
T_1	16.0	
U_1	18.0	
V_1	20.0	
W_1	22.0	
X_1	24.0	
Y_1	26.0	

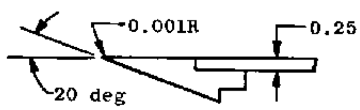
a. Rectangular Model

Fig. 2 Model Details



All Dimensions in Inches

O Pressure Tap
Δ Mass Injection Port
+ Thermocouple



Section A-A

Instrument Number	x, in.	Type Instrument
1	8.5	Pressure
2	11.0	
3	16.0	
4	21.0	
5	25.0	
6	31.0	
7	21.0	
8	21.0	
9	25.0	
10	25.0	
11	31.0	
12	31.0	
A	9.0	Injection Port
B	13.0	
C	18.0	
D	23.0	
A_1	9.5	Thermocouple
B_1	12.0	
C_1	14.5	
D_1	17.0	
E_1	19.5	
F_1	22.0	
G_1	24.5	
H_1	27.0	
J_1	29.5	
K_1	32.0	
L_1	19.5	
M_1	22.0	
N_1	22.0	
O_1	24.5	
P_1	24.5	
Q_1	27.0	
R_1	27.0	
S_1	29.5	
T_1	29.5	
U_1	32.0	
V_1	32.0	

b. Delta Model

Fig. 2 Concluded

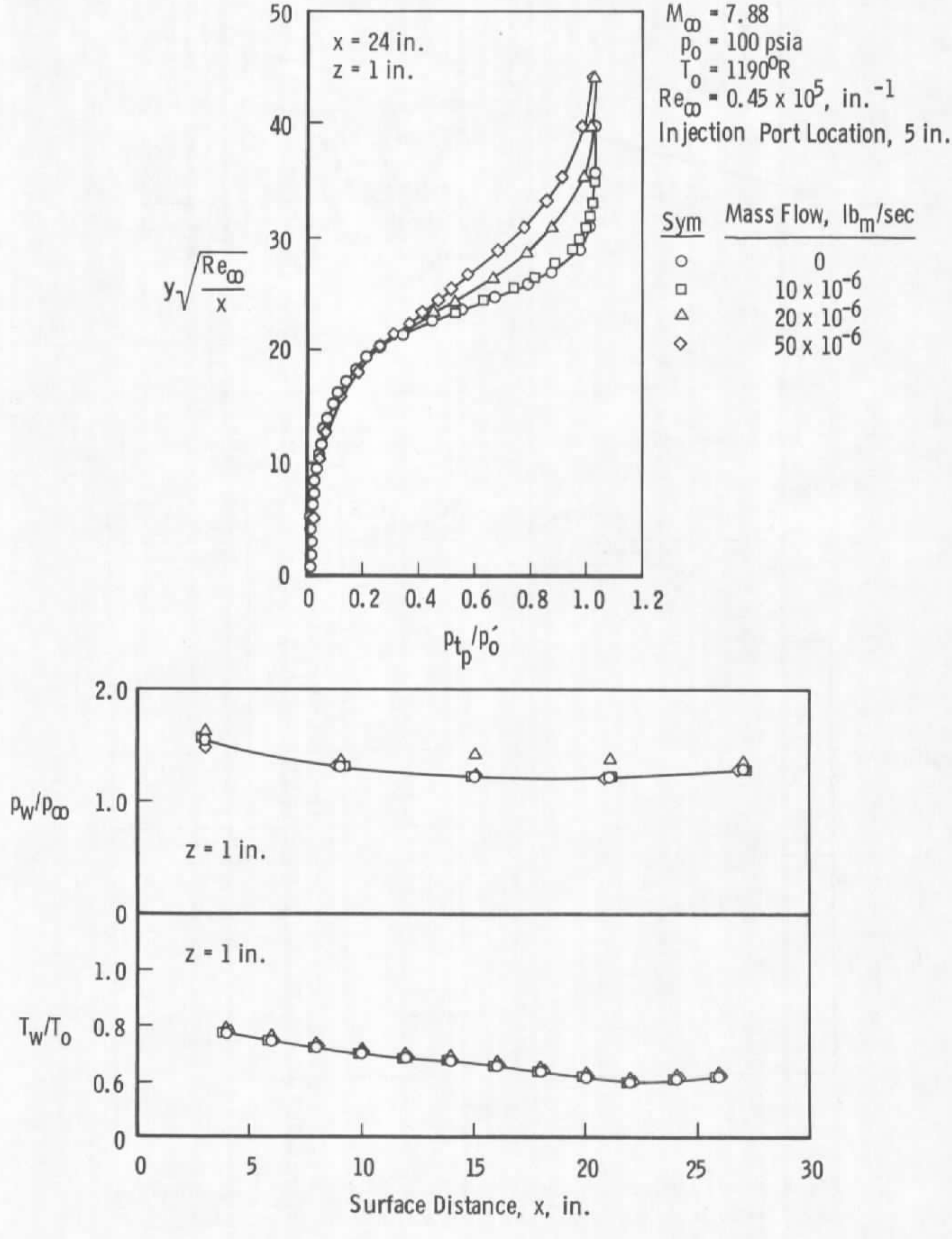


Fig. 3 Effect on Boundary-Layer Pitot Pressure Profiles of Mass Injection on a Sharp Rectangular Plate at Mach 8

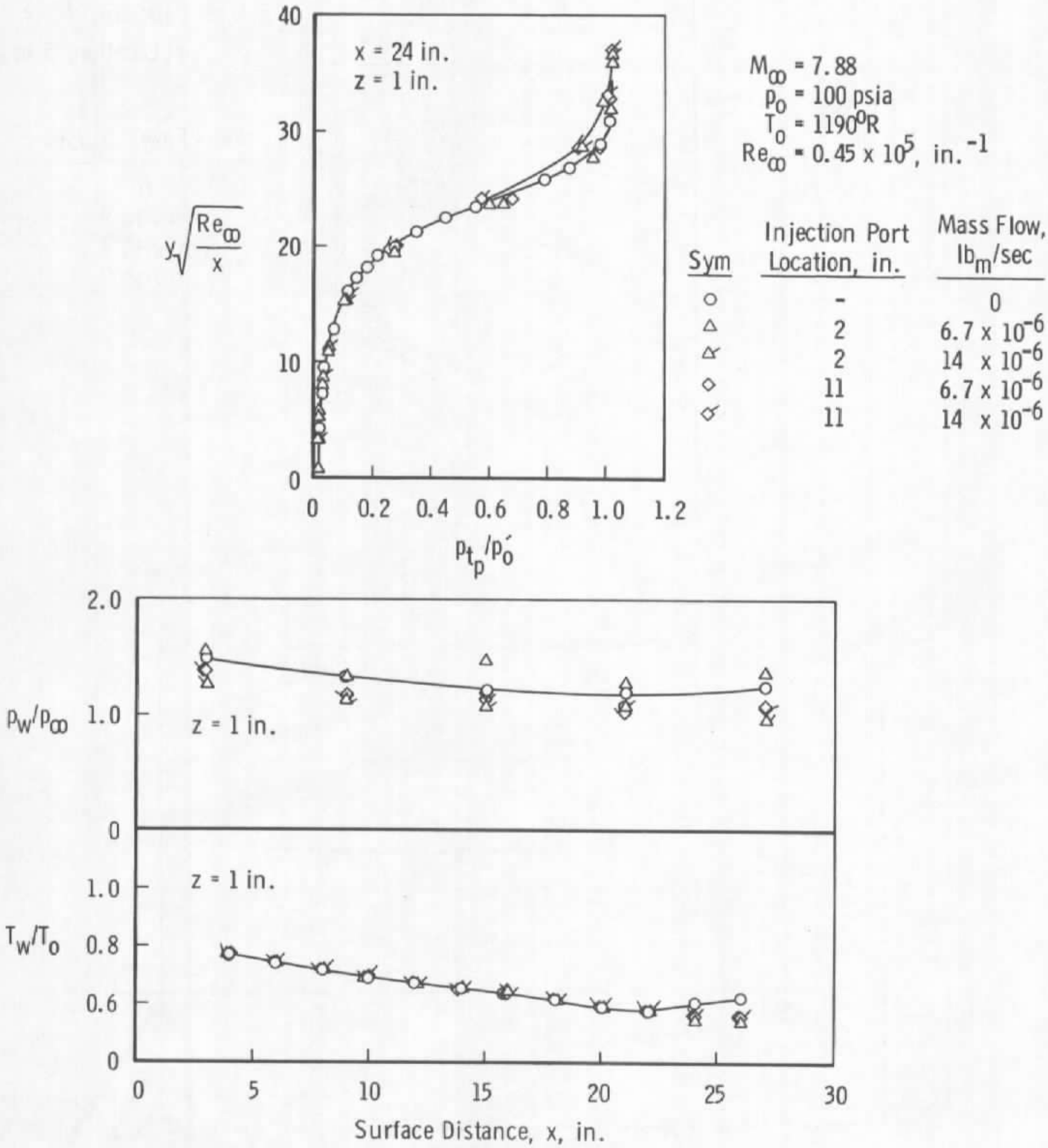


Fig. 4 Effect on Boundary-Layer Pitot Pressure Profiles of Mass Injected at Different Locations on a Sharp Rectangular Plate at Mach 8

Sym	M_∞	p_o, psia	T_o, °R	Re_∞, in.$^{-1}$ x 10^{-5}
○	7.88	100	1190	0.45
△	7.92	200	1240	0.85
◇	7.95	300	1265	1.22

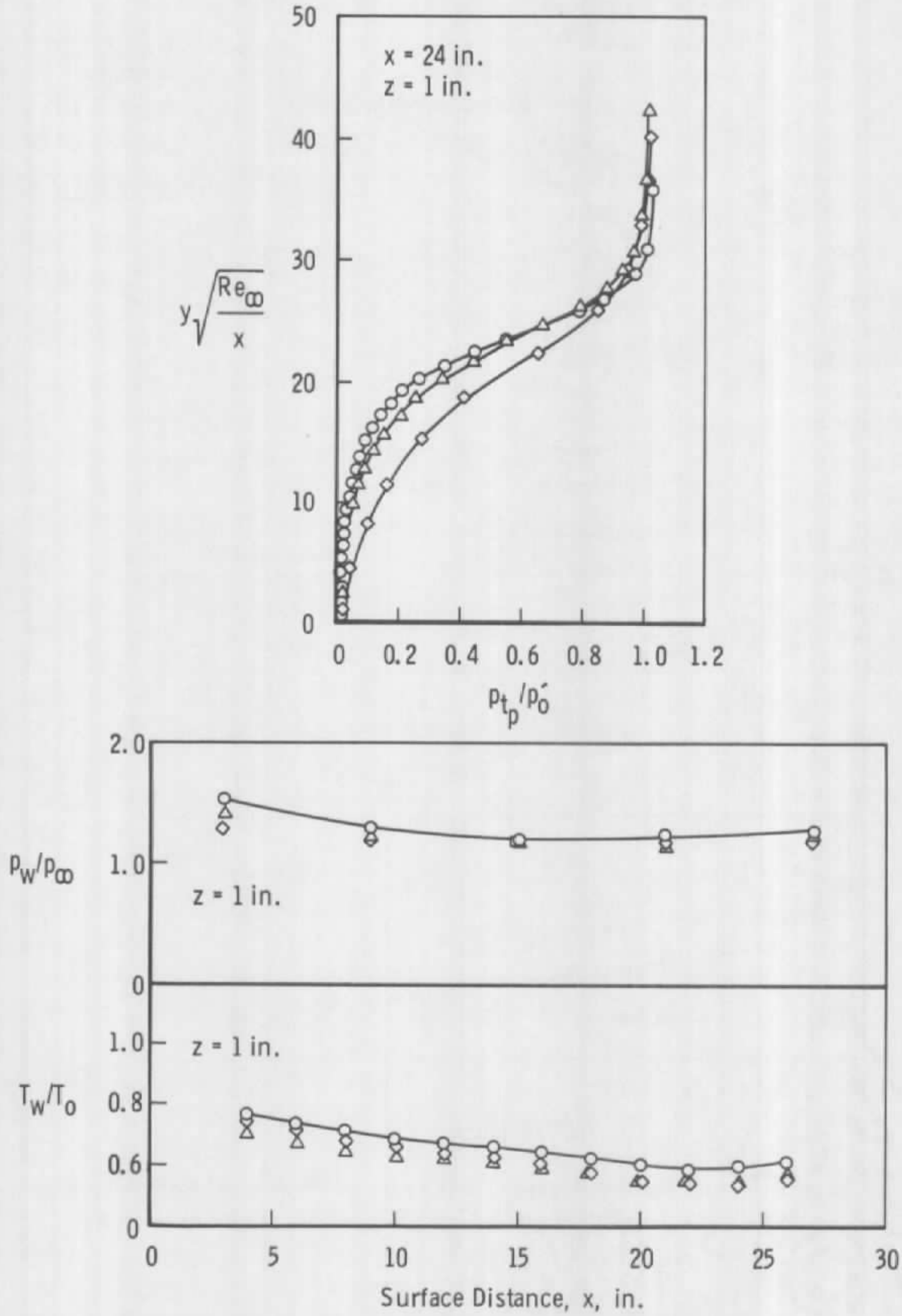


Fig. 5 Effect of Variations in Free-Stream Reynolds Number on Boundary-Layer Pitot Pressure Profiles for a Sharp Rectangular Plate at Mach 8

TABLE I
TEST CONDITIONS

	Model Configuration		
	Sharp Rectangular	Blunt Rectangular	Delta
Nominal Mach 6			
Unit Reynolds, in.$^{-1}$ x 10^{-5}	0.29 to 2.42	0.29 to 4.25	0.60 to 4.25
Angle of attack, deg	-5 to +15	-5 to +15	-5 to +15
Trip location, in.	2 to 7	2 to 7	9 to 18
Trip mass flow, lb_m-sec^{-1} x 10^6	3.6 to 15.0	2.5 to 73.0	3.0
Profile locations, in.	6 to 24	6 to 24	9 to 33
Nominal Mach 8			
Unit Reynolds, in.$^{-1}$ x 10^{-5}	0.45 to 3.20	0.45 to 3.20	0.98 to 3.20
Angle of attack, deg	-5 to +15	-5 to +15	-5 to +10
Trip location, in.	2 to 11	2 to 5	9 to 18
Trip mass flow, lb_m-sec^{-1} x 10^6	6.7 to 50.0	6.7 to 50.0	10.0 to 20.0
Profile locations, in.	6 to 24	6 to 24	7 to 30
Nominal Mach 10			
Unit Reynolds, in.$^{-1}$ x 10^{-5}	1.27 to 1.80	0.68 to 1.80	0.68 to 1.80
Angle of attack, deg	-5 to +10	+10	-5 to +10
Trip location, in.	2 to 7	2 to 11	9 to 23
Trip mass flow, lb_m-sec^{-1} x 10^6	100.0	60.0	340.0
Profile locations, in.	12 to 24	16 to 24	4 to 30

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13 ABSTRACT

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14 KEY WORDS	LINK A		LINK B		LINK C	
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air injection						
boundary layer						
hypersonic flow						
laminar						

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